Anderson localization of spinons in a Heisenberg spin-1/2 chain

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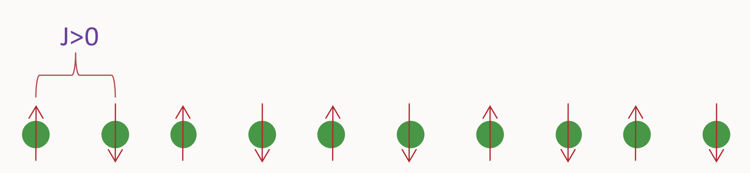
Abstract

Anderson localization (AL) is a fundamental phenomenon in disordered systems which has been oberserved for light, microwave, ultrasound and cold atoms. Here we report the observation of AL in a magnetic system, namely the spin-1/2 Heisenberg chain material Cooper benzoate. We synthsized cooper benzoate single crystals and performed ultralow temperature specific heat and thermal conductivity measurements. Spinon excitation signal persists down to 50 mK for specific heat. For spinon thermal condcutivity κ_s, we find a linear temperature dependence down to 300 mK. Below 300 mK, κ_s/T decreases rapidly and vanishes at about 100 mK, which is a clear evidence for AL.

Physics of Heisenberg spin-1/2 chain

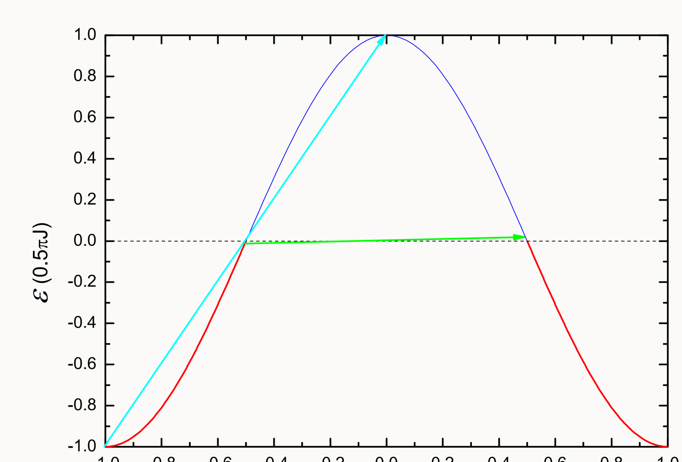


$$H = J\sum_i S_i \bullet S_{i+1}$$

$$H = J\sum_i \{ \frac{1}{2}(S_i^+ \bullet S_{i+1}^- + S_i^- \bullet S_{i+1}^+) + S_i^z \bullet S_{i+1}^z \}$$

Jordan-Wagner transformation

$$H = J\sum_i \{ \frac{1}{2}(c_i^\dagger c_{i+1} + c_{i+1}^\dagger c_i) + (c_i^\dagger c_i - \frac{1}{2})(c_{i+1}^\dagger c_{i+1} - \frac{1}{2}) \}$$



Dispersion relation: $\epsilon_k = \frac{\pi}{2}J|\sin(ka)|$

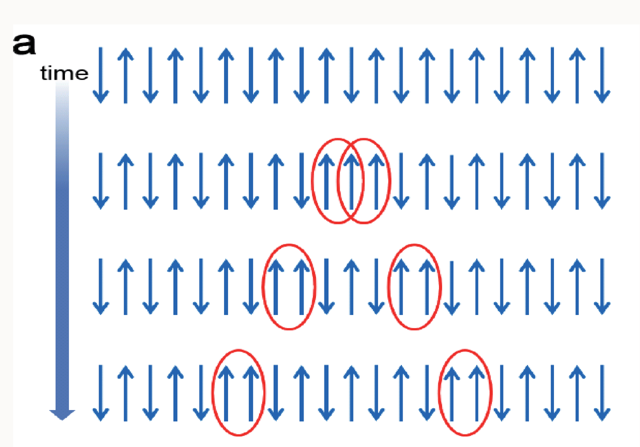
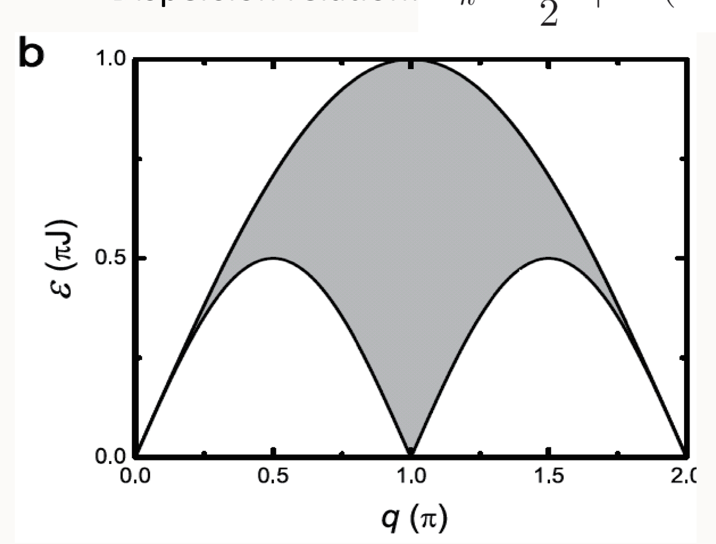
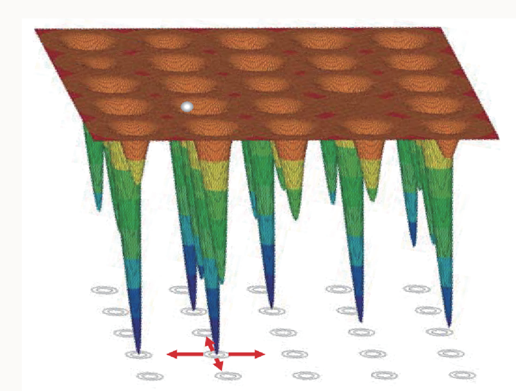


illustration of a pair of spinon excitations

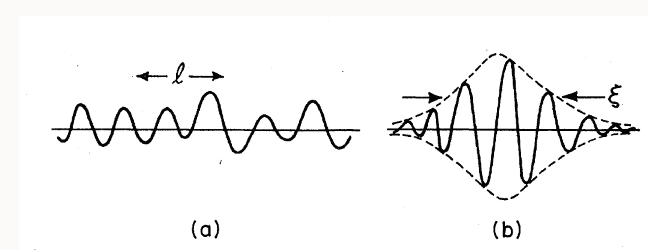


Two-spinon continuum spectrum

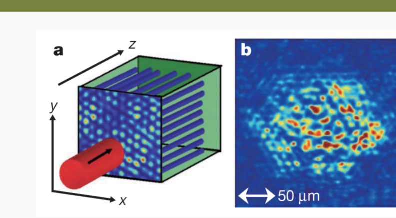
Anderson localization and realizations



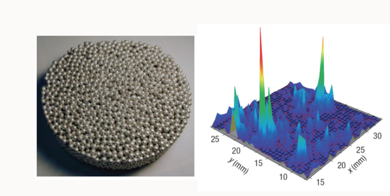
The Anderson model. Increasing the randomness of potential would change the electron from mobility to a complete halt. (P. W. Anderson, 1958)



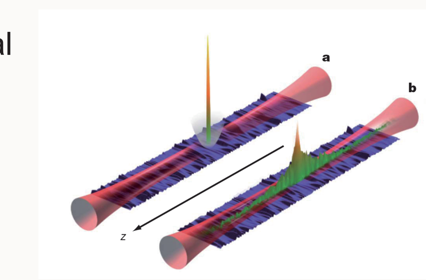
Typical wave function of (a) extended state and (b) loacalized state $\psi(r) \propto \exp(|r - r_0|/\xi)$



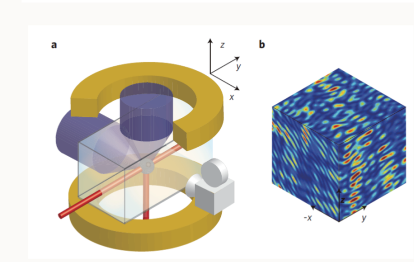
Anderson localization of light



Anderson localization of ultrasound

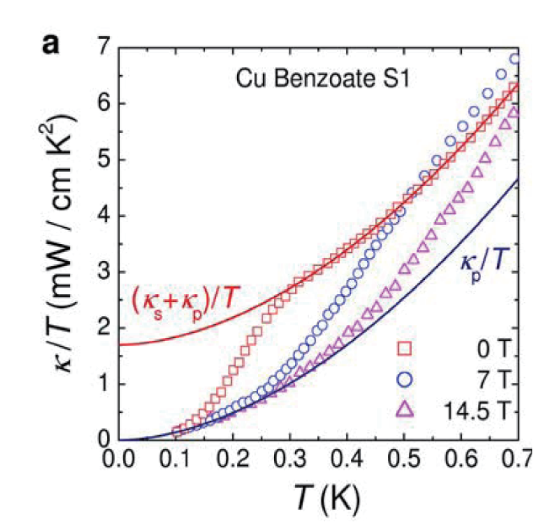


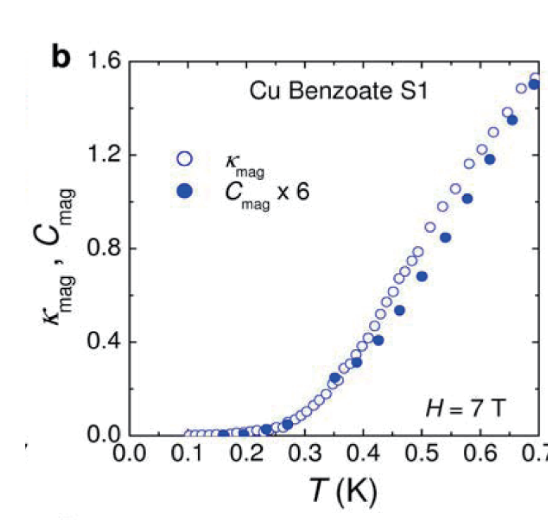
Anderson localization of 1D cold atoms



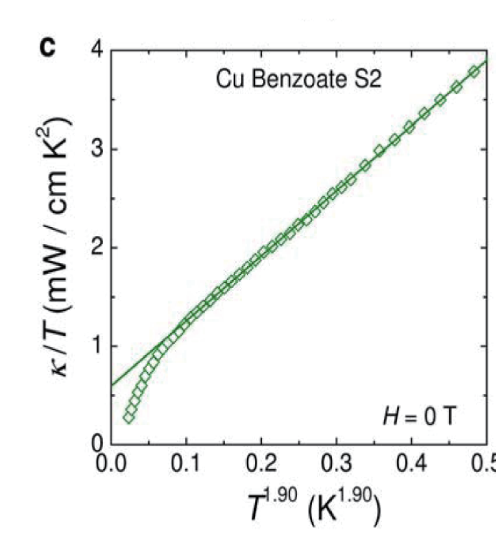
Anderson localization of 3D cold atoms

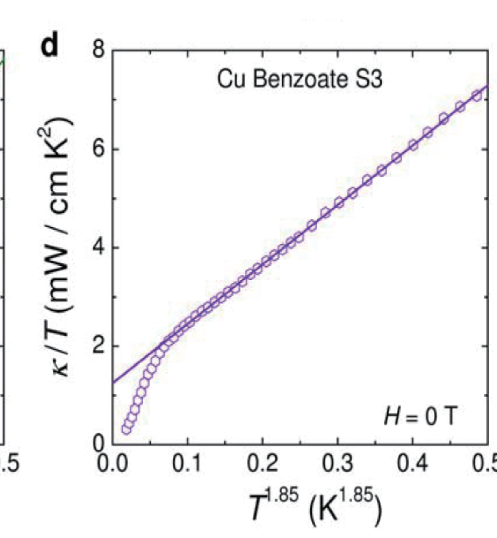
Thermal conductivity of Copper benzoate



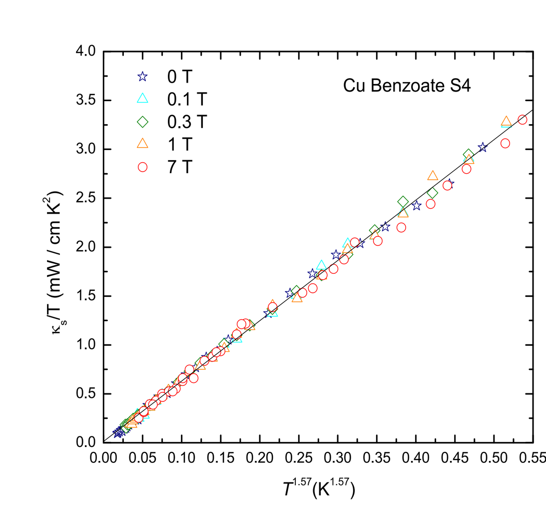


(a) Thermal conductvitiy of S1 under magnetic fields from 0 to 14 T. The thermal current is along the chain direction. κ can be seperated into spinon part κ_s and phonon part κ_{ph}.
(b) κ_s under 7 T almost overlaps with $6xC_s$ indicating constant mean free path of the underlying excitations.



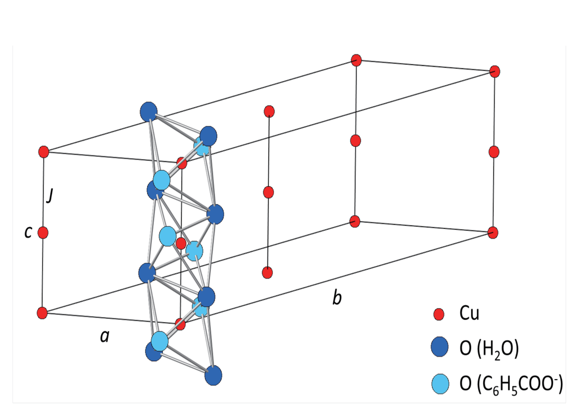


Thermal conductivity of S2 and S3, the thermal current is along the chain

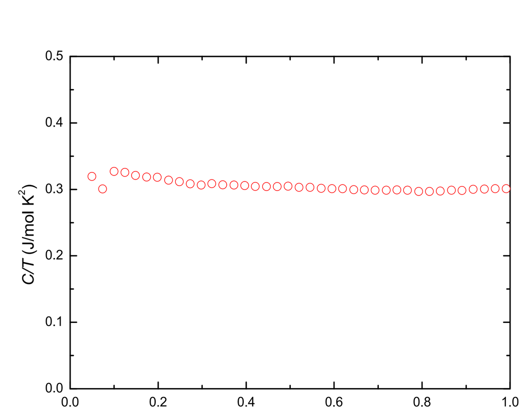


Thermal conductivity of S4 in which the thermal current is perpendicular to the chain. κ does not change under magnetic fields.

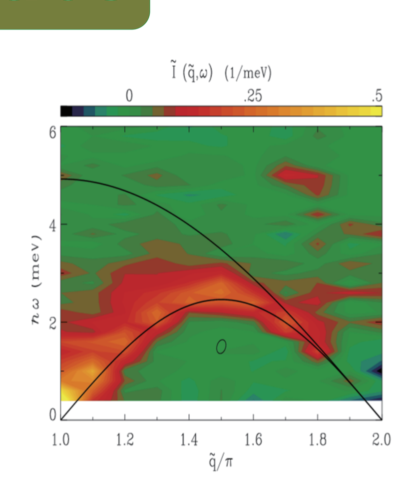
Copper benzoate: magnetic properties



Crystal structure of copper benzoate, the chain is along the c-axis with magnetic exchange constant J = 18.6 K



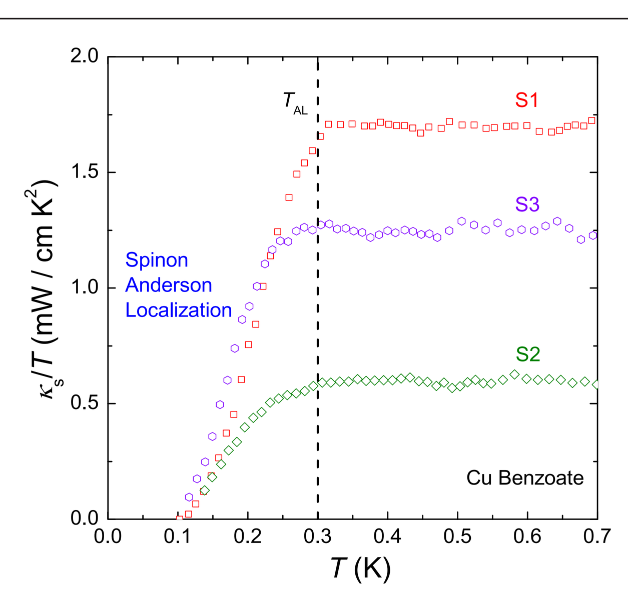
Specific heat of copper benzoate down to 50 mK, with no Neel order occurs. The linear coeficient is in perfect agreement with the theoretical value 0.298 J/mol K²



Neutron scattering spectrum

Discussions

Spinon thermal conductivity of copper benzoate single crystals S1, S2, and S3 in H = 0 T, plotted as κ_s/T versus T. The different value of κ_s/T above 300 mK suggests that the spinon mean free path in copper benzoate is sample dependent. Below 300 mK, κ_s/T decreases rapidly and vanishes at about 100 mK, which gives a strong evidence for spinon Anderson localization. The onset temperature of the spinon localization T_{AL} remains at about 300 mK when the mean free path of spinons differs by 3 times between S1 and S2.



References

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[5] S. S. Kondov *et al*., Science 334, 66 (2011)
[6] B. Y. Pan *et al*., arXiv 1208:3803

Summary

In summary, we have investigated spinon Anderson localization in copper benzoate, an ideal compound of spin-1/2 antiferromagnetic Heisenberg chain. While a linear temperature dependence of spinon specific heat C_S is observed down to 50 mK, the spinon thermal conductivity κ_S only shows linear temperature dependence down to 300 mK. Below 300 mK, κ_s/T decreases rapidly and vanishes at about 100 mK, which is interpreted as a strong evidence for Anderson localization. We believe that our work is the first example of Anderson localization for magnetic excitations, thus opens a new window for studying such a fundamental phenomenon in condensed matter physics.